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The Persistence of Epiphyseal Scars in the Distal Radius in Adult Individuals

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Introduction

The estimation of chronological age is a fundamental step in the development of a biological profile during the process of forensic human identification. Formed from data pertaining to the characteristics of ancestral origin, biological sex, chronological age and living stature, the biological profile enables a targeted search of missing persons' records in an attempt to aid in the identification of the remains of an individual.

Age estimation is facilitated by the relationship between the development and maturation of the hard tissues of the body, i.e. teeth and bone, and chronological age. Consequently, the accuracy of the estimated age is dependent on the strength of the relationship between skeletal or dental development and maturation and chronological age. It is acknowledged that the strength of the relationship between chronological age and dental development is greater than that between skeletal development and chronological age [1,2]; however due to post-mortem loss, the dentition is not always available for analysis [3]. It is therefore necessary to establish and test methods of age estimation that are applicable to skeletal development in the absence of the dentition.

Although many methods and approaches to skeletal age estimation exist [4-13], it is prudent to take certain conditions into consideration when selecting the most appropriate method to apply [14]. The applicability of a method or approach to a given case is dependent on a number of factors including the condition of the remains (e.g. fresh, decomposed or skeletal); the approximate age of the individual (i.e. juvenile or adult); and the anatomical regions represented by the remains [14]. Assessments of age can be undertaken based on an examination of physical remains or through the analysis of images derived from medical imaging technologies including Computed Tomography (CT)[10,15], radiography [5,7-9,16,17], ultrasonography (US) [13,18,19] or Magnetic

Resonance Imaging (MRI) [20,21]. The application of medical imaging technologies to the process of skeletal age estimation facilitates an examination of not only the surface or gross morphology of the bone but also the underlying structure including trabecular organisation [22] and density [23], thereby allowing the examination of features or characteristics which may not be visible from gross inspection alone.

The epiphyseal scar, which forms at the locus of the former growth plate, is one characteristic of the internal osseous architecture that may be observed using medical imaging technologies including radiography and CT. The potential misinterpretation of epiphyseal scars as transient features was first suggested by Cope in 1920 [24] who noted the frequent persistence of epiphyseal scars in adult individuals in whom epiphyseal fusion had long since completed. Despite the persistence of this feature being reported in multiple anatomical regions [25-28], the general consensus within the literature has been that following the completion of epiphyseal fusion, epiphyseal scars will become obliterated, resulting in a lack of distinction between the diaphysis and epiphysis when observed radiographically [5,16,17,28,29]. As a result of this perception, the transition between an observable epiphyseal scar and its disappearance has been incorporated into the staging criteria of several methods of age estimation [30-32]. There is however a paucity of published literature in relation to the potential persistence of the epiphyseal scar in this region.

The importance of age estimation from the skeleton extends beyond the identification of deceased individuals to include the estimation of age in living persons for whom chronological age is not known or is disputed. The age of an individual is inextricably linked to their rights and responsibilities under law, their access to social welfare assistance and the responsibilities of official agencies towards the individual [33].

There are however some instances in which the age of an individual is unknown and consequently, their entitlement to resources or their degree of responsibility for their actions cannot be determined. In these instances, it may be necessary to estimate the age of the individual through various approaches including the analysis of a radiographic image of the left hand and wrist [12]. As a result of the importance placed on the examination of the distal radius in skeletal age estimation, it is appropriate to consider the potential error in the interpretation of the epiphyseal scar as a transient structure.

A recent study which examined epiphyseal scars in the adult tibia suggested that the relationship between the degree of obliteration of the epiphyseal scars of the proximal and distal tibia and chronological age was not statistically significant [34]. The results of this study supported those obtained by Weiss *et al.* [35] who, in a study of the first metatarsal, observed a persistent epiphyseal scar in 38% of individuals. As a result of these findings, Weiss *et al.* advised the use of caution in the interpretation of epiphyseal scars in relation to chronological age[35]. When combined with the literature pertaining to the use of epiphyseal scars as surgical landmarks [36], the findings of the studies by Weiss *et al*. [35] and Davies *et al.* [34] indicate that the association between chronological age and the persistence or obliteration of the epiphyseal scar may not be consistent or appropriate in all skeletal areas.

A number of methods of age estimation utilise the transition between the presence of an observable epiphyseal scar and its disappearance as a demarcation of minimum chronological age [30,37]. While there is some evidence that the epiphyseal scar of the distal radius may become obliterated in some individuals, there is a paucity of information pertaining to the statistical significance of the relationship between the

degree of obliteration or persistence of the epiphyseal scar and chronological age. This article will augment the existing body of literature pertaining to the persistence of the epiphyseal scar of the distal radius and investigate the relationship between chronological age, biological sex and the persistence of the epiphyseal scar.

Materials and Methods

A sample of 616 radiographic images of the distal radius was obtained from separate individuals who had attended various medical facilities within NHS Tayside between 2008 and 2011. The images included in this study represented both sides of the body and had been obtained for the purpose of clinical assessment of injury. Individuals who were noted as having experienced atypical skeletal development; an injury affecting the region of the distal radial growth plate or the epiphyseal scar; or a chronic illness were excluded from the sample. Only those radiographs in which no abnormality was diagnosed were included in the study.

It has been reported in the literature pertaining to dry bone studies that epiphyseal scars are likely to disappear within 2 years of the completion of epiphyseal fusion [28]. To ensure that the findings of this study represent a valid picture of the persistence of epiphyseal scars in adult individuals, the sample radiographs included in this study were obtained from patients aged between 20 and 50 years inclusively. Each single year cohort was represented by 20 radiographic images where each sex and side of the body was represented by 5 images. The only exceptions to this were in the female left wrist cohort representing 32 years of age and the male left wrist cohort representing 44 years of age each contained 3 individuals. These limitations were imposed by the availability of suitable radiographs within the clinical image dataset.

To facilitate the examination of certain characteristics in relation to the persistence of the epiphyseal scar, the sex of the individual, the date of birth (DoB) and the side of the body from which the image was obtained were recorded. The date on which each image was taken (DoI) was also noted. From this information, the chronological age of the individual was calculated using Microsoft Excel™. Due to the clinical nature of the radiographs and the regulations pertaining to patient confidentiality, each radiograph was anonymised prior to its inclusion in the study sample and ethical approval for the use of anonymised clinical data was obtained from the Tayside NHS Trust.

Due to limitations imposed on the study by the available patient information, it was not possible to include data pertaining to the ancestral origin and socio-economic status of individuals within the sample group. Data obtained from official reports of the Scottish Government state that the population of Tayside is approximately 98.1% white and that there is approximately 16-19% relative deprivation across the three council areas included in the area covered by NHS Tayside [38]. As the study sample represented a cross-section of the Tayside population, there is no reason that the demographic distribution of the clinical population would differ significantly from that of the general population.

Adobe Photoshop® was used to divide each radiograph into six equally spaced tracks which spanned from the medial to the lateral extremities of the distal radius (Figure 1). The epiphyseal scar within each track was then assigned a score between 0 and 2, according to the degree of persistence observed. A score of 0 was assigned if no epiphyseal scar was observed; a score of 1 was assigned if a partial or fenestrated scar was observed and a score of 2 was assigned if the observed epiphyseal scar completely traversed the track. The total persistence score (TPS) was then calculated for each

individual as the sum of the scores assigned to each of the tracks i.e. a maximum score of 12 would be indicative of an epiphyseal scar that traversed all tracks across the full width of the bone. From this information, the percentage of individuals in whom some remnant of the epiphyseal scar of the distal radius was retained was calculated. This was termed the Total Persistence Rate (TPR).

The data obtained from the initial image analysis phase was used to calculate the persistence of the epiphyseal scar within the medial, central and lateral regions of the bone. These regions corresponded to tracks 1 - 2, 3 - 4, and 5 - 6 respectively. The sum of the persistence scores assigned to each pair of tracks was then termed the regional persistence score (RPS). From this analysis, the mean, maximum and minimum persistence scores found within each area of the bone could be determined and any potential pattern in the variation of the persistence of the feature could be assessed.

The TPS and RPS values assigned to each individual were recorded using Microsoft Excel and analysed using IBM SPSS statistics software. The relationships between these data and the chronological age and sex of the individual; and the side of the body from which the radiograph was obtained were assessed using General Linear Model (GLM) analyses.

Intra-observer Analysis

A subset of radiographs from 30 females and 30 males was selected at random from the main study set for analysis of intra-observer consistency in the assignment of TPS. Each image was re-assessed by a single observer, and the consistency between the two sets of observations was calculated. A pair of observations was deemed to be consistent if the TPS values assigned on the first and second occasions were within 2 scores. The

percentage of consistent findings was calculated for females and males. Following this, a one way analysis of variance (ANOVA) test was conducted to assess the statistical significance of the variation between the assessments made on each occasion.

Inter-observer analysis

The subset of images used in the analysis of intra-observer consistency was similarly assessed by three additional observers, each of whom held a PhD. in either anatomy or forensic anthropology. The observers represented varying levels of experience in age estimation and the interpretation of radiographic images. Observer 1, although not experienced in radiographic interpretation or skeletal age estimation, had significant experience in line and pattern recognition. Observer 2 was a highly experienced forensic anthropologist who specialises in skeletal age estimation and has significant experience in radiographic interpretation. Observer 3 was a highly experienced forensic anthropologist. Each observer completed a single round of assessments on each of the female and male image subsets. The TPS values were then calculated and compared with those assigned by each of the other observers and the degree of variation between each pair of observers was determined. A series of one way ANOVA was undertaken to assess the statistical significance of the variation between the TPS values assigned by the three observers.

Results

Intra-observer and inter-observer analysis

Analysis of the data obtained from the assessment of intra-observer consistency showed that a single observer consistently assigned persistence scores as defined by this study on 80% of occasions in females and 77% of occasions in males. The

maximum variation between the TPS values assigned during the intra-observer analysis occurred in the male sample and was ±7. This degree of variation was however found on only 1 occasion. An analysis of variance test indicated that the degree of intra-observer variation in the TPS values assigned was not statistically significant in either the female (P=0.847) or male (P=0.112) data sets.

Analysis of the data obtained from the assessment of inter-observer consistency suggested that the degree of variation between the TPS values assigned to the female sample by three observers was not statistically significant (P=0.054); however the degree of variation found within the data derived from the analysis of the male sample was found to be statistically significant (P=0.048). The highest degree of consistency in both the female and male samples was between observers 1 and 2 where percentage agreements of 87% and 93 % were attained respectively. The lowest percentage agreement was found between observers 1 and 3 in the female sample and observers 2 and 3 in the male sample, where values of 63% and 77% were found respectively.

Main analysis

The distributions of TPS in the female and male samples are presented according to the percentage of the total sample and mean chronological age in Figures 2 and 3 respectively. The results of a Shapiro-Wilk analysis indicated that these distributions were not normal in either the female (P<0.001; W-statistic=0.956) or male (P<0.001; W-statistic=0.930) samples. Overall, 86% of females and 78% of males were found to have retained some remnant of the epiphyseal scar in the distal radius. A one-way ANOVA suggested that the variation in TPS between females and males was not statistically significant (P=0.100).

The relationship between the degree of persistence of the epiphyseal scar and chronological age was assessed through the application of a series of GLM analyses. The use of GLM analyses also enabled the relationship between biological sex, side of the body and the persistence of the epiphyseal scar to be quantified. These data, presented in Table 1, suggest that when considered as independent variables, there were no statistically significant relationships between the persistence of the epiphyseal scar and the chronological age (P=0.190) or biological sex (P=0.072) of the individual or the side of the body from which the radiograph was obtained (P=0.684). As these variables may not be considered as independent, it was necessary to determine the relationships between these factors and TPS when considered as co-variables. The results of these analyses indicated that the factors of chronological age, biological sex and side of the body do not influence the persistence of the epiphyseal scar of the distal radius significantly when considered as independent or dependent factors.

To assess the localised variation in the persistence of the epiphyseal scar within an anatomical area, the mean RPS value assigned to each of the medial, central and lateral regions of the distal radius were calculated and the results presented in Table 2. The greatest mean RPS values were found in the central region of the epiphyseal scar in both the female (1.41) and male (1.26) samples. Within both the central and lateral regions, higher mean RPS values were found in the female sample. Within the medial region however, the mean RPS value of the male sample exceeded that of the female by 0.01. In addition to this rudimentary analysis, the statistical significance of the variation in persistence score assigned to each region was calculated for both data sets through the application of a series of one way ANOVA analyses.

The variation between the medial and central; and central and lateral regions was found to be statistically significant in both the female ($P<0.001$; $P=0.012$) and male ($P=0.043$; $P<0.001$) cohorts. Although the significance of the variation in the persistence of the epiphyseal scar in the central and lateral regions was similar between males and females, the variation observed between the medial and central regions in females greatly exceeded that found within the male sample. The variation between the medial and lateral regions was not statistically significant in either the female ($P=0.201$) or male ($P=0.081$) cohorts.

To account for the regional variation in the epiphyseal scar which was attributable to chronological age, biological sex or side of the body, a series of GLM analyses were conducted. A summary of the statistically significant results of these analyses are presented in Table 3. Through assessment of the relationship between these factors and the regional persistence of the epiphyseal scar within each anatomical region, the potential effect of factors other than those included in this study could be examined.

As was observed in the analysis of TPS, side of the body was not observed to exhibit a statistically significant relationship with RPS ($P=0.571$). In contrast to the previous analyses however, statistically significant relationships were observed between the remaining factors of chronological age and biological sex and RPS where P values of <0.001 and 0.012 were found respectively. Although chronological age exhibited the strongest relationship with RPS, the co-efficient of determination of this interaction was 0.022. This finding indicates that the majority of variation in the regional persistence of the epiphyseal scar in the distal radius is not directly attributable to the factors examined in this study when considered independently. Results of further GLM analyses however indicated that the interaction between chronological age, biological sex and

side of the body explained the greatest amount of variation in the regional persistence of the epiphyseal scar ($P=0.002$; $R^2=0.081$). The exclusion of side of the body from this analysis resulted in an increase in the statistical significance of the relationship between chronological age, biological sex and the regional persistence of the epiphyseal scar ($P<0.001$); however this also resulted in a reduction in the co-efficient of determination ($R^2=0.052$). The weakness of the relationships between the factors considered by this study and the persistence of the epiphyseal scar indicates that variables other than those examined in this analysis may influence the persistence or obliteration of this feature in the distal radius.

Discussion

An assessment of skeletal age in living individuals may be undertaken for a number of reasons, and may involve cases of a disputed minor, i.e. a person whose status as an individual aged younger than 18 years of age is under dispute, attempting to enter a country without documentation; or an individual attempting to defeat the ends of justice by means of deception relating to their true age [21,39]. According to the recommendations of the working group on forensic age diagnostics (AGFAD), an estimation of age in living individuals in criminal proceedings should include an assessment of the skeletal development of the left hand and wrist [12,40-42]. As the distal radius is the final component of this anatomical area to achieve skeletal maturity, this region has been considered in detail by a number of methods of skeletal age assessment [5,30,37,43].

The methods by which the development and maturation of the distal radius is assessed frequently employ scoring systems which compare the observed skeletal morphology with standardised criteria [30,37]. The final maturity criteria often applied by such

methods are the completion of epiphyseal fusion with the retention of an observable epiphyseal scar in the distal radius (Schmeling *et al.* stage 4) and subsequently, the obliteration of this epiphyseal scar, resulting in a radiographic continuity between the diaphysis and epiphysis of the distal radius (Schmeling *et al*. stage 5) [30,37]. Although this approach to classification of the epiphyseal scar could be considered subjective, the results of the intra-observer and inter-observer analyses conducted in this study indicate that the variation in observations of the epiphyseal scar is unlikely to be of significance in the majority of cases. As a subjective method however, there is the potential that the experience of the observers could influence the degree of variation in the observed persistence of the epiphyseal scar.

It is accepted that a minimum age at which these criteria occur may be appropriate in some cases of skeletal age estimation; however some reference texts have assigned a maximum age at which Schmeling stage 4 has been found [30,37]. The inclusion of a maximum age for this stage infers that a persistent epiphyseal scar would not be observed beyond this age. While the obliteration of the epiphyseal scar of the distal radius certainly occurs in some individuals, this study found that 86% of females and 78% of males examined retained some remnant of the epiphyseal scar in this anatomical area. While the total persistence rates of the epiphyseal scar in the distal radius are lower than those previously observed in the proximal and distal tibia, these values indicate that complete obliteration of the epiphyseal scar in this anatomical region is unlikely to occur, irrespective of sex [34].

As this study was limited to the investigation of the epiphyseal scar in adults between 20 and 50 years, these findings can only indicate that an epiphyseal scar may be retained until at least 50 years of age, as documented by the Greulich/Pyle atlas. This

expands on the work of Baumann *et al.* [30] where the referred maximum age for a distal radial scar of 30 years evidently occurred as a function of the maximum age of the individuals within the study sample. As persistent epiphyseal scars were observed in individuals throughout the range of ages included in both this study and that of Baumann *et al*., [30]it does not appear to be appropriate, based on these results, to assign a maximum age of persistence to the epiphyseal scar of the distal radius.

One of the primary considerations for methods of skeletal age estimation is the relationship between the factor under examination and the chronological age range wherein it may appear; and consequently, the accuracy of the method in estimating age. Analysis of the presence of an epiphyseal scar and its obliteration in the distal radius and chronological age in a test sample ranging from 20 to 50 years suggested that this relationship was not statistically significant. Although these findings should be interpreted cautiously due to the cross-sectional nature of the study sample, the result indicates that some remnants of the epiphyseal scar, as well as the complete obliteration of the feature may be found throughout this age cohort. To summarise: The only statistical value attributable to such an open ended adult feature is the minimum age of appearance, the age of which is beyond the range utilised in this study. This, in conjunction with the high persistence rate of the epiphyseal scar observed in both females and males indicates that some remnant of the epiphyseal scar is likely to persist in a majority of individuals. The weak relationship between chronological age and TPS also indicates that the obliteration of the epiphyseal scar of the distal radius may be under the influence of factors other than chronological age. The absence of a statistically significant relationship between chronological age and the level of obliteration or persistence of the epiphyseal scar in the distal radius differs from the

findings of a previous study which examined the epiphyseal lines in the proximal and distal tibia [34]. The variation in the significance of the relationship between chronological age and the obliteration of the epiphyseal scar between skeletal areas indicates that, in addition to those influences being exerted on a systemic level such as the regulation of calcium metabolism, additional factors which exhibit a more localised expression may exert an effect on the degree of remodelling to which the epiphyseal scar is exposed [44,45].

As the results of this study indicate that the persistence or obliteration of epiphyseal scars in the distal radius may be influenced by factors other than chronological age, an analysis of the relationship between biological sex and the persistence or obliteration of the epiphyseal scar was undertaken. The results of this analysis showed that this relationship was not statistically significant when considered independently or when the combined influence of chronological age and biological sex on the persistence of the scar was assessed. The potential effects of biological sex on the persistence or obliteration of the epiphyseal scar centre on the relationship between biological sex and bone remodelling.

There are a number of routes through which the process of bone remodelling can be affected by the sex of the individual including the action of systemic hormones, body mass and physical activity. As this study has shown that there is no statistically significant relationship between biological sex and TPS in the distal radius, it is suggested that these factors do not elicit a significant response in bone remodelling in the distal radius in relation to the obliteration of the epiphyseal scar. This is further supported by the absence of a statistically significant difference in the TPS values assigned to females and males in this study. This is in contrast to the findings of a

previous study which examined the proximal and distal tibia in which a statistically significant relationship between biological sex and TPS was found in both areas [34]. The variations observed in the significance of the relationship between chronological age, biological sex and the persistence of the epiphyseal scars in the distal radius, and proximal and distal tibia further supports the hypothesis of a localised influence on the remodelling of the epiphyseal scar, for example trajectory of mechanical loading of the bone [34].

The potential role of localised factors in the obliteration of the epiphyseal scar in the distal radius was investigated further through an analysis of the variation in the persistence of the epiphyseal scar between three discrete (medial, central and lateral) regions of the distal radius. In both female and male cohorts, the highest mean regional persistence score occurred in the medial third of the bone. Analysis of the variation in the persistence of the epiphyseal scar between the medial, central and lateral regions of the radius showed that the variation between both the medial and central; and central and lateral regions was statistically significant. The variation in the persistence of the epiphyseal scar between the medial and lateral thirds of the bone however was not statistically significant in either females or males. The presence of statistically significant variation between regions of the distal radius indicates that the obliteration of the epiphyseal scar in this anatomical region may be influenced by localised factors which vary across the expanse of the bone.

The variation in the obliteration of the epiphyseal scar observed within the regions of the distal radius adds further weight to the hypothesis that the obliteration of the epiphyseal scar is affected by localised factors, in addition to those influences related to the endocrine system and normal metabolic activity [44,45]. Comparison of the findings

of this study, as an example of the upper limb, with that of the proximal and distal tibiae, as examples of the lower limb indicate that there is a higher degree of retention of the epiphyseal scar in the lower limb than the upper limb within the samples studied [34]. It is acknowledged that the rate of bone remodelling varies throughout the skeleton [45-47]. This may partially explain the degree of variation between the upper and lower limbs; however, the mechanostat theory should be taken into consideration [48-50]. It has been suggested that the rate of bone remodelling within a region is related to the degree of force applied i.e. an increase in applied load results in an increase in bone remodelling rate as a result of volumetric changes within the cancellous bone [51,52]. To stimulate bone remodelling however, the applied load must deviate from the normally applied load [52]. As the lower limb experiences a higher normal load, the so-called "set-point" of bone remodelling from which deviation is measured will also be higher and a greater deviation may be required in order to stimulate the process of remodelling which, if uncontrolled, would ultimately result in the obliteration of the scar [45,53]. This theory may also explain the variation in the persistence of the epiphyseal scar in the distal radius found between females and males, and between the medial, central and lateral regions of the bone, as the force applied by the musculature of the forearm, in addition to the load transmitted through the wrist joint, will vary between males and females and between the regions of the bone.

Conclusion

The obliteration of the epiphyseal scar in the distal radius has, in recent years, formed a component part of numerous methods of skeletal age estimation, often accompanied by a maximum age at which a persistent epiphyseal scar may be observed. The assumption on which the inclusion of this maturity criterion in such methods had been based, and

particularly the inclusion of a maximum age of persistence, was however untested. The findings of this study augment those previously published by other authors and indicate that some remnant of the epiphyseal scar may persist until at least the 5th decade of life. In addition, analysis of the obliteration of the epiphyseal scar in this anatomical region has shown there to be no statistically significant relationship between the obliteration of the epiphyseal scar of the distal radius and chronological age. The findings of this study confirm that only the minimum age of appearance of a marker of ultimate formation may be used for the purpose of skeletal age estimation, as represented, for example, by a fully ossified distal radius with, or without, the presence of an epiphyseal scar.

Conflicts of Interest

There are no known conflicts of interest

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